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Observations on the Electric Discharge of *Torpedo occidentalis.*

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(Text-figures 1–4).

In June of 1941 a specimen of *Torpedo occidentalis* was brought to the New York Aquarium and several more were brought in during the next few weeks. These were all large, in excess of 15 kilograms in weight, and one was very large, 61 kilograms, probably a record size.

A few electrical measurements were made on the first of these fish within a few hours after its arrival at the Aquarium. Circumstances unfortunately delayed further observations, and before they could be resumed all these specimens died. Two others, however, remained available at Point Lookout, Long Island, at the fish pier of Mr. Robert Doxsee, from whom the former specimens had been obtained. To avoid possible injury to these fish by the handling necessary in transporting them, it was thought advisable to observe them without bringing them to the Aquarium. Through the courtesy of Mr. Doxsee a cathode-ray oscillograph and accessory equipment were set up at Point Lookout, partly on the pier and partly on the live well floating alongside, in which the fish were kept. Observations under these conditions were somewhat difficult and, what was more unfortunate, the two fish, after having been for several weeks in the live well, were evidently in very poor condition.

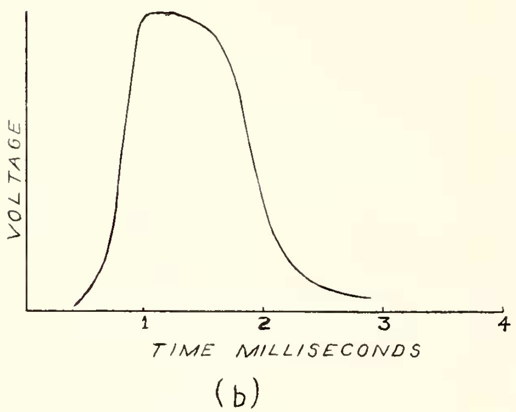
Although for these reasons our observations are necessarily rather fragmentary, they appear to contain some information not recorded elsewhere, and a brief report on them would thus seem to be worth while.

The first specimen showed a peak voltage of 220 volts when the dorsal and ventral surfaces of its electric organ on one side were connected to the oscillograph on "open circuit," so that no appreciable current was drawn except what flowed in the circuit made through the body of the fish. Except for the voltage drop caused by this current, the full electromotive force would have been measured in this way. Probably the electromotive force was not much higher than the measured peak voltage, and may therefore be taken as approximately 220 volts.

In this species, however, the electromotive force appears to vary widely with the condition of the fish. The measurements made on this specimen were so arranged as to keep the fish out of water as short a time as possible. Actually they were all completed in about one minute. We can not say how many discharges were made in this time; there were certainly several hundred, possibly a thousand. Whether from being out of water, from fatigue, or from the handling incidental to the measurements, the peak voltage on open circuit dropped 60 volts during this time. More striking still was the difference between this specimen and the two observed at Point Lookout. Although these were of about the same size as the first specimen, their peak voltage on open circuit was only about 25 volts.

The oscillographic traces produced by the first specimen were not recorded photographically but only noted visually. Even so, certain differences between the traces made by the torpedo and those made by the electric eel and described elsewhere[1] were evident. The discharge of the torpedo did not show so sudden a rise in voltage or so abrupt a transition from a rapidly rising to a gently falling voltage. A few photographic

[1] Coates, C. W., R. T. Cox, and L. P. Granath. The Electric Discharge of the Electric Eel, *Electrophorus electricus* (Linnaeus). *Zoologica,* Vol. XXII (Part 1), No. 1, April 5, 1937.



Text-fig. 1. **a.** Oscillographic trace of the electric discharge of *Torpedo occidentalis.* **b.** Oscillographic trace of the discharge of *Electrophorus electricus.*

traces were obtained of the discharge of one of the two specimens observed at Point Lookout. Text-fig. 1(a) was drawn from one of these: 1(b), shown for comparison, was made from a photographic trace produced by the electric eel. In copying from the photographs, the time scale was made the same for the two figures. The scales of voltage are different between the two, having been so chosen as to make both peaks of the same height. It is apparent that the duration of the discharge of the torpedo was longer than that of the discharge of the electric eel. But it should be repeated that the discharge shown for *Torpedo* is that of a specimen in poor condition.

The electric organs of *Torpedo occidentalis,* like the large organs of the electric eel, throw off discharges in trains, the separate discharges following one another at an interval of a millisecond or so. With the specimen first observed there were more discharges in one train than the three, four, or five commonly observed with the electric eel. Without a photographic record, it can not be said just how many there were. Probably there were at least a dozen in the average train. The photographic traces obtained at Point Lookout, perhaps because of the poor condition of the specimen, showed fewer discharges to the train than were observed with the first specimen.

The observed regularity of the discharges within a train and in successive trains suggested that the same quantity of tissue was active in each discharge, and it is natural to suppose that the entire organ connected to the oscillograph was active together. Also it was possible to show plainly that the right and left organs discharged simultaneously. The method used was that employed before to measure the time lag between the discharge in anterior and posterior portions of the large organs of the electric eel, and it had been described elsewhere.[2] One of the vertically deflecting plates in the oscillograph tube being joined to one of the horizontally deflecting plates, their junction was connected to a large sheet of metal on which the torpedo rested, the ventral surfaces of both organs being over the plate. Two smaller sheets, some distance apart on the dorsal surface of the fish, covered the two organs on that surface. These two sheets were connected respectively to the other two deflecting plates of the oscillograph tube, so that the discharge of the organ on one side would produce a vertical deflection and that on the other side a horizontal deflection. (Strictly speaking, the discharge on one side would produce a nearly vertical, that on the other a nearly horizontal, deflection, the complete separation of the two deflections being prevented by leakage of the current across the body of the fish from one side to the other. An auxiliary observation, in which one sheet was over the organ on one side while the other was over non-electric tissue, was used to estimate the possible effect of this leakage). Both organs discharging exactly together would produce equal vertical and horizontal deflections, and thus would combine to make an oscillographic trace along a straight line at 45 degrees with either the vertical or the horizontal direction. A small time lag between the discharges of the two organs would change the trace into a loop, the width of the loop being greater the greater the time lag. Actually the trace appeared simply as a straight line. Had there been a time lag as great as .0001 sec. it should have been detectible by this method.

Some muscular activity accompanies the discharge of *Torpedo occidentalis.* The fish, which is flat and roughly disk-like in shape, showed distinct tremors around the periph-

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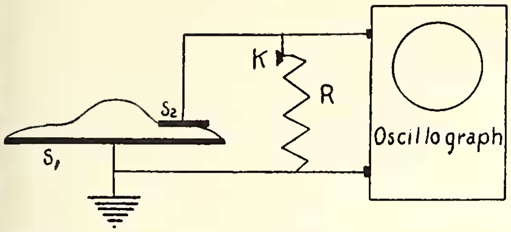
[2] Coates, C. W., R. T. Cox, W. A. Rosenblith, and M. Vertner Brown. Propagation of the Electric Impulse Along the Organs of the Electric Eel, *Electrophorus electricus* (Linnaeus), *Zoologica,* Vol. XXV (Part 2), No. 14, July 3, 1940.

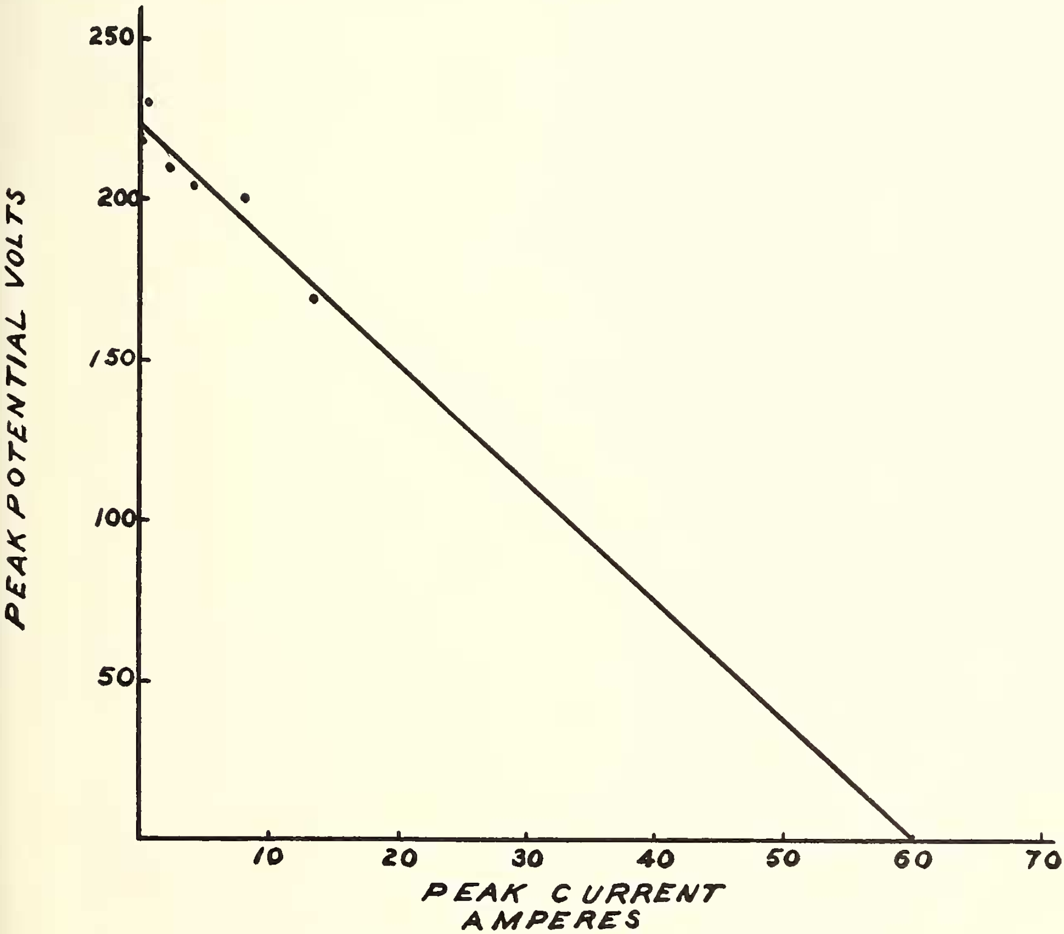


Text-fig. 2. Diagram of the electric circuit for the measurement of the peak voltage of the discharge.

ery of the body when the discharge occurred, although it is not certain whether these were directly before or during the train of discharges. This activity caused the margins of the wings to curl upward, sometimes more than 10 cm. from the surface on which the fish was lying. During a long series of discharges these margins were raised throughout the period with accompanying tremors starting from the thick central region of the body and spreading outward to the periphery.

With the electric eel, no muscular activity, or at least none comparable to this in extent, accompanies the discharge.

The circuit used in the measurements made on the first specimen is shown in Text-fig. 2. The fish rested on a metal sheet S_1, which was at ground potential. The wet ventral surface made good electric contact with this sheet. The smaller sheet S_2 was shaped to cover the dorsal surface of the electric organ on one side of the fish, firm pressure and moisture making good electric contact here also. These electrodes were connected to the oscillograph, so that the voltage between them could be measured. By closing the switch K the variable resistance R could be connected across the organ so as to draw a current during its discharge. The resistance R being known and the potential difference V at the peak of the discharge being measured, then by Ohm's law the cur-



Text-fig. 3. Graph of peak voltage V against peak current I.

rent I at the peak of the discharge is given by the equation

$$V = IR$$

Also the peak power P supplied by the electric organ to the resistance is given by

$$P = VI$$

One set of measurements completed before the fish showed signs of fatigue, is given in Table I below.

TABLE I.

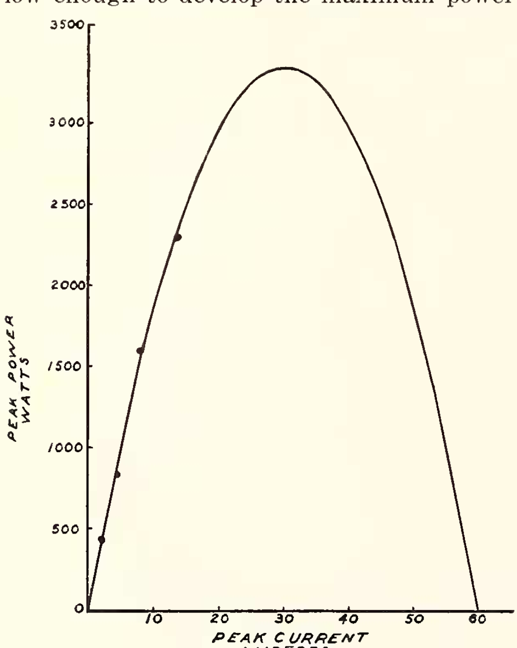
Peak Voltage, Current and Power with Various Resistances.

R ohms	V volts	I amperes	P watts
∞*	220	0	0
370	230	0.6	140
100	210	2.1	440
50	205	4.1	840
25	200	8.0	1600
12.5	170	13.6	2310

* Open circuit.

That these data are not precise is clear enough from the fact that the peak voltage on open circuit was observed as less than that across a resistance of 370 ohms. Such irregularities are caused both by the inaccuracy of the observation and the variability of the fish.

It will be noticed that the power rises with falling resistance over all the range of the observations. The reason for this is that without prior experience with the species we failed to provide calibrated resistances low enough to develop the maximum power



Text-fig. 4. Graph of peak power P against peak current I.

of the discharge. But some inference beyond the observations may be made, as is illustrated in Text-figs. 3 and 4.

In Text-fig. 3 the values of V and I from Table I have been plotted and a straight line has been drawn among the plotted points. This construction may be justified by Ohm's law, and it is supported by many observations we have made on electric fish of other species. Values of V and I taken from this graph were used to compute the power P for the graph shown in 4, in which the plotted points again represent values from Table I.

The greatest current of which the organ is capable would be obtained by a complete short circuit, that is, by having R, and hence also V and P, practically zero. According to the graphs this current is 60 amperes. It is clear from the figures that the extrapolation is doubtful, since this value of the current is more than four times the highest reached in the observations. Probably, however, the organ is capable of a current of at least this order of magnitude. This does not mean that so great a current is normal to the fish. It is probable that the organ discharging in sea water carries something like half of its maximum current, since that would be the condition for the greatest release of power in the water.

For the maximum power Text-fig. 4 gives a value a little more than 3 kilowatts. The extrapolation here is more trustworthy than that for the maximum current, since this power is only 30 per cent. higher than the highest observed. Since the two electric organs discharge together, we have 6 kilowatts or about 8 horsepower as the electric power of both organs at the peak of the discharge. Of course it must not be overlooked that this is the peak power, and the average power, even during the discharge, would probably be some 25 or 30 per cent. of this. The average during a train of discharges would again be less than the average during one discharge, and would probably be 500 to 1,000 watts for both organs. Finally it should be noted that the trains of discharges do not appear to be given often.

The cross-sectional area of the organ on either side, in a plane parallel to the ventral surface, was about 250 square centimeters. The current was in a direction perpendicular to this plane, and its value for maximum power was, as shown above, about 30 amperes. Hence the current density at maximum power was about 0.12 ampere per square centimeter.

The mass of the organ on each side was about 2,000 grams. The maximum power released outside the organ being 3,000 watts, the maximum power per gram of the organ must have had an instantaneous value around 1.5 watts or one-third of a calorie per second.